ESTIMATION OF BONDLINE DIMENSIONS IN ADHERED METAL JOINTS USING ULTRASONIC LAMB WAVES: FINITE ELEMENT STUDIES OF UNDERLYING PHYSICAL PHENOMENA

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INTRODUCTION

The automotive industry is increasingly interested in using adhesive bonding in the construction of body shell assemblies. Adhesive joints offer some significant potential advantages over conventional welding techniques, including improved strength and stiffness, greater flexibility in designs, and reduced costs. The NDE requirements associated with the introduction of adhesive bonding include the confirmation during construction that the dimensions of the adhesive in the joint are within specified tolerances. In the common case of a lap joint, illustrated in Figure 1, the key dimensions are the bond thickness and the overlap length.

The simplest method to measure the bond dimensions using ultrasound is to perform a scan over the area of the joint using a signal which is normally incident to the outer surface of one of the adherends. Techniques which could be used for the measurement of the bond properties, including the thickness, at each position in such a scan have been widely researched [1,2]. However, direct access to the joints is sometimes not possible because of the geometry of the assembly or cladding materials. An alternative approach to the inspection, which may also be faster, is to use Lamb waves which propagate from one side of the joint to the other. The concept is illustrated in Figure 1. A transmitter excites a Lamb mode in one of the adherends, then a receiver in the other adherend detects the signal which is transmitted across the joint. The properties of the joint are then inferred from their influence on the transmitted signal. Previous publications which have addressed the interaction of Lamb waves with lap joints include both adhesively bonded and spot welded joints [3,4].

Unfortunately the measurement of the dimensions of the bond from the Lamb wave signal is not straightforward, because of the very complicated nature of the transmitted signals. As will be shown in more detail shortly in this paper, the transmission is affected by

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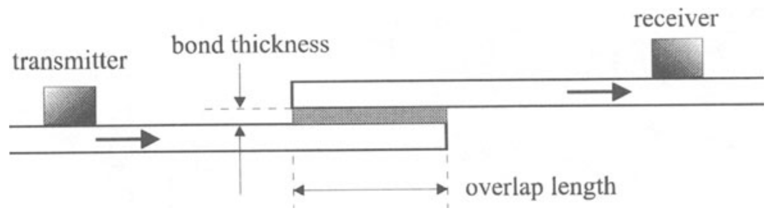

Figure 1. Arrangement for Lamb wave testing of lap joint.

mode conversion to more than one mode in the overlap region, followed by reverberations along the length of the overlap region. Consequently there is currently no simple way to measure the dimensions directly from the received signal. However success has been achieved using artificial neural networks (ANNs) to interpret the signals. Challis and co-workers have demonstrated, both for lap and T-form adhesive joints, that trained ANNs can recognise the key bond dimensions in more than 90 % of trials. This work is reported in a companion paper in these proceedings [5].

Although the success of the ANN technique offers an effective and early practical solution to the NDE requirements, there remains significant scientific value, as well as curiosity, in understanding more about the physics of the phenomena of the transmission across the joints. Improved understanding may potentially be used to further develop the ANN schemes for greater efficiency and reliability, and may also lead to the possibility of direct measurements of some parameters of joints from the received signals. The motivation of the investigation which is reported here was therefore to develop some understanding of what takes place in the transmission across an adhesive joint, taking as a specific example the s_0 mode in a lap joint.

The investigation was undertaken using time domain Finite Element simulations. The modelling was conducted using the general purpose program FINEL which was developed at Imperial College [6]. Four-noded linear plane strain elements were used to model a section through the joints in the plane of the wave propagation. Explicit time marching was employed, assuming a diagonal mass matrix. The dispersion curves and mode shapes were calculated using the program DISPERSE, also developed at Imperial College [7,8].

TRANSMISSION OF THE s_0 MODE ACROSS A JOINT

Before studying the phenomena which occur within the overlap region of a joint, we present predictions for the overall transmission of the s_0 signal across a joint, for ranges of both the bond thickness and the bond length. A simple lap joint between a pair of 1.6 mm aluminium plates was studied. Separate solutions were predicted for 80 different cases, covering each combination of 8 bond lengths and 10 bond thicknesses. The bond lengths ranged from 2 mm to 30 mm, the bond thicknesses from 0.2 mm to 2 mm. A centre frequency of 625 kHz was chosen, corresponding to a frequency-thickness product of 1 MHz-mm in the adherends. The dispersion curves for the adherends are plotted in

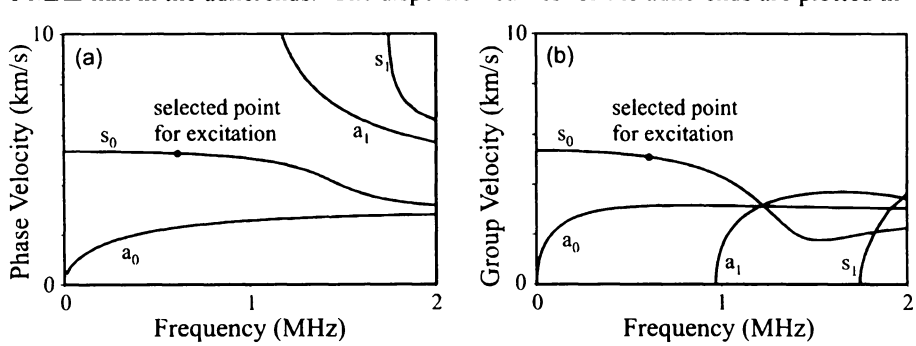

Figure 2. (a) Phase velocity and (b) group velocity dispersion curves for 1.6 mm thick aluminium plate.

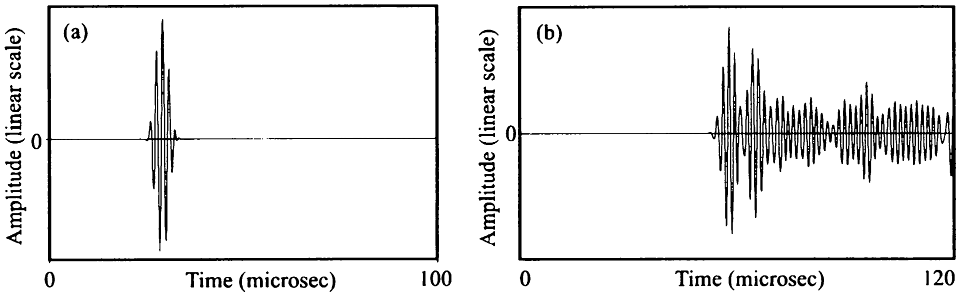

Figure 3. (a) Input signal; (b) received signal after transmission across joint.

Figure 2, showing that the s_0 mode is reasonably non-dispersive at this point. The curves also show that the a_0 mode is the only other mode present. The existence of another mode at this frequency becomes significant when considering the received signal because energy transmitted through the joint may propagate into the receiver plate in both modes. The aim of the study was to predict the transmission of just the s_0 mode; it therefore had to be separated from the a_0 mode on reception.

Examples of time domain signals from the study are shown in Figure 3. Figure 3(a) shows the input signal which was used identically for all of the cases and consisted of 5 cycles at the centre frequency of 625 kHz, in a Hanning window. This signal was prescribed as a displacement history for the in-plane displacements at all of the nodes at the incident end of the plate. Figure 3(b) shows an example of the received signal at one of the nodes on the surface of the receiver plate, for a joint with bond length of 26 mm and bond thickness of 1.4 mm. This illustrates the complicated nature of the transmission.

We identify three phenomena which contribute to the complication of the received signal: (1) in general, several possible modes can propagate within the overlap region, interfering with each other and each transmitting energy at a different velocity; (2) the modes within the overlap region can reflect as well as transmit at the ends of the overlap, so that they reverberate over the length of the overlap, emitting energy into the receiver plate at each reverberation (this is why the received signal has a long duration); (3) both s_0 and a_0 modes are transmitted into the receiver plate.

Some further examination of the transmission was performed using a two-dimensional Fourier transform (2DFFT), a technique which decomposes a spatial series of signals into

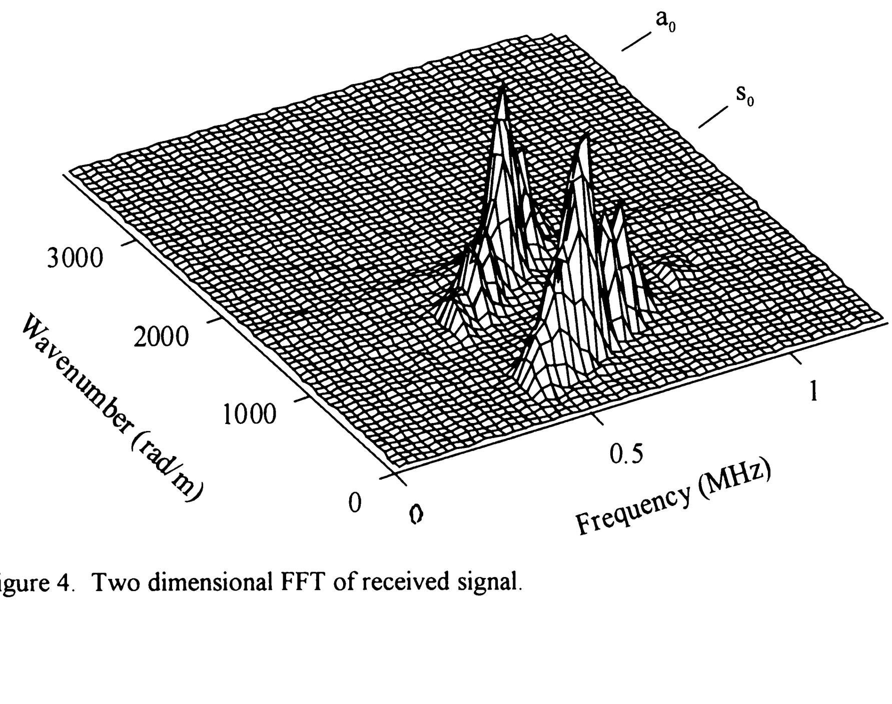

Figure 4. Two dimensional FFT of received signal.

both frequency and wavenumber domains [9]. Keeping to the same example of joint dimensions, the displacements in the direction normal to the plate were recorded at 64 equally-spaced nodes on the surface of the receiver plate. The 2DFFT plot is shown in Figure 4. The plot clearly separates the contributions due to the s_0 and a_0 modes. It also reveals evidence of the reverberations: instead of being smooth profiles, the spectra show minima and maxima along the frequency axis, a feature characteristic of a series of echoes or repeating signals.

It is not obvious how a simple scalar measure of such a signal can be extracted as a transmission coefficient for comparison of the different joints. We chose to apply Parseval's theorem in two dimensions. This theorem states that the power content of a signal can be determined by summing the squares of the Fourier components which make up this signal. In the two dimensions of ω-k space we define the Lamb wave transmission coefficient across a complex boundary as being the sum of squares of ω-k components in the transmitted wave, divided by those of the incident wave. We express the coefficient in dB:

$$T = 10 \log \frac{\sum_{\omega}\sum_{k} B_{\omega k}^{2}}{\sum_{\omega}\sum_{k} A_{\omega k}^{2}} \tag{1}$$

where B refers to the amplitudes of displacement in the direction normal to the plate for the transmitted wave, and A for the corresponding amplitudes for the incident wave. If the summations are carried out for the same incident and transmitted mode and the same displacement component, then this formula expresses the power transmission coefficient of that mode. However, it is important to be aware that this is not the case if the incident and transmitted modes are different. This is because the relationship between the amplitude of displacement in the direction normal to the plate and the power of the wave is different for each mode. For the same reason it is not valid to perform either of the summations in the expression over more than one mode in the ω-k space. We are interested in the received s_0 mode, so the transmission coefficient for each joint was calculated by performing the summation over the s_0 part of the 2DFFT plot.

The power transmission coefficient results for all of the joints are plotted in Figure 5. The plot shows that when the bond thickness is small (below 1mm), the transmission

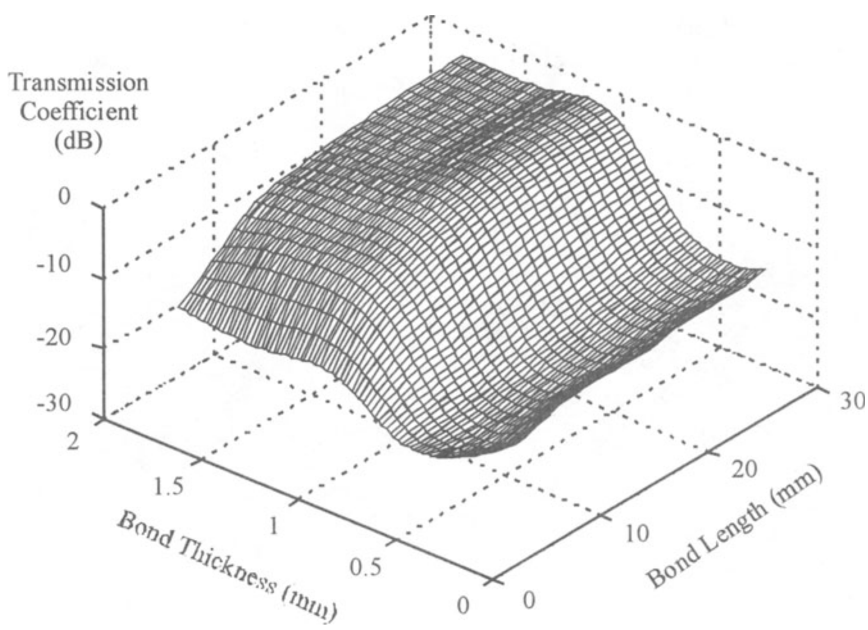

Figure 5. Power transmission coefficient for s_0 mode across lap joint.

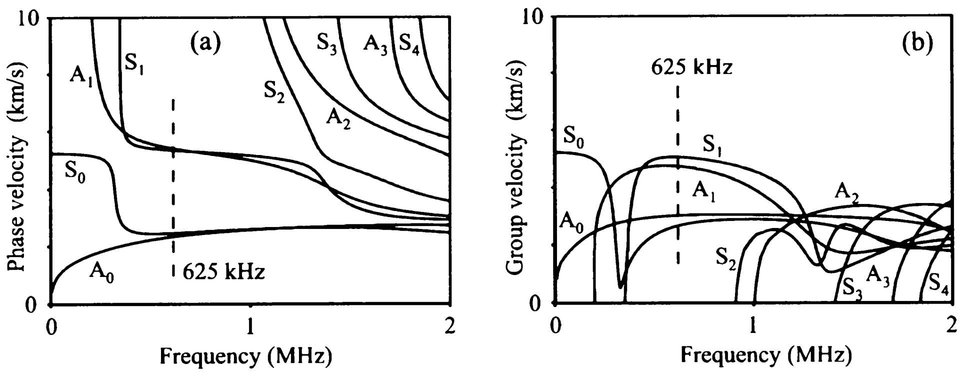

Figure 6. (a) Phase velocity and (b) group velocity dispersion curves for overlap region.

coefficient is relatively low. If the bond thickness is 1mm or above, then the transmission coefficient starts off low at small bond lengths and rises relatively rapidly with bond length. For bonds whose lengths are larger than 15 mm and thicknesses are larger than 1 mm, the transmission coefficient is fairly constant at about –2 dB. Similar behaviour in the variation of the transmission coefficient with bond length was observed by Rokhlin [3] in a numerical and experimental study of the Lamb wave transmission coefficient between two metal sheets coupled together by a water layer.

IDENTIFICATION OF MODES TRANSMITTING ENERGY IN OVERLAP REGION

A joint with a bond thickness of 0.4 mm was used for a more detailed study of the waves in the overlap region. The dispersion curves for the modes which can exist in the overlap region of this joint are shown in Figure 6. At the centre frequency of the study there are now four modes, two symmetric and two antisymmetric. These are labelled with capital letter, S_0, S_1, A_0, A_1, in order to differentiate them from the modes in the simple plates which are labelled with the lower case letters s_0, a_0. In principle, the incident s_0 mode can mode convert to any or all of the four modes in the overlap region.

A two-stage Finite Element model was used to examine the role of these four "carrier" modes in the overlap region. The model is illustrated schematically in Figure 7. In the first stage, the s_0 mode was excited as usual in the transmitter plate, then each of the four carrier modes was received separately in the overlap region. The separate reception of the symmetric and the antisymmetric modes was achieved by detecting, respectively, the in-plane and out-of-plane displacements at the centre line of the joint. The separation of the resulting pairs of modes was achieved by using a sufficiently long length of overlap in the model for them to separate in time, exploiting their large differences in velocity. In the second stage, the s_0 mode was detected separately in the receiver plate for each of the four carrier modes incident in the overlap region.

Combination of the results of the two-stage model yields the contribution of each of the four carrier modes to the overall transmission, shown in the frequency domain in

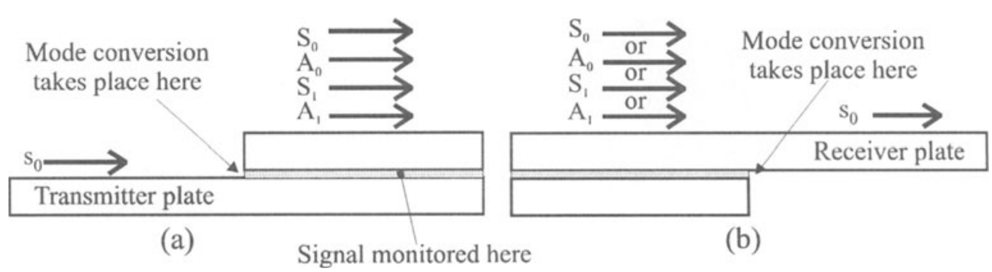

Figure 7. Finite element models used for studying mode conversion: (a) s_0 mode incident at start of joint, (b) carrier modes incident at end of joint.

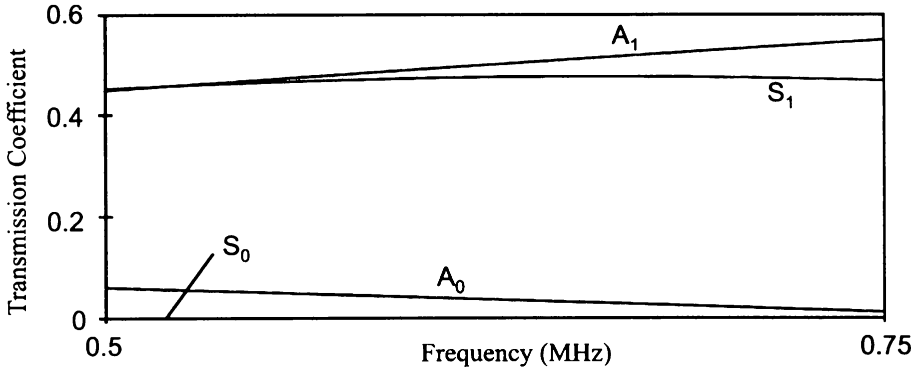

Figure 8. Contributions from each of the carrier modes to the overall transmission of s_0 across the joint.

Figure 8. In this figure the transmission coefficient is simply the displacement amplitude of the s_0 mode in the receiver plate divided by the amplitude of the same displacement component of the s_0 mode in the transmitter plate. Interestingly, the predictions show that the S_1 and A_1 carrier modes dominate strongly, and approximately equally, the contributions from the zero-order modes being practically negligible.

The reason why the S_1 and A_1 carrier modes dominate can be seen by comparing the mode shapes of the input mode to the mode shapes of the carrier modes. These are shown in Figure 9 for a frequency of 625 kHz. We should expect to excite modes in the overlap region if the mode shape in the bottom layer of the overlap region (the part of the overlap region occupied by the transmitter plate) is similar to the mode shape in the transmitter plate. It can be seen that the S_1 and A_1 modes in the bottom layer have very similar mode shapes to the s_0 mode in the transmitter plate whereas the mode shapes of the S_0 and A_0 modes are totally different.

SIMPLIFIED PREDICTIONS OF TRANSMISSION OF s_0 MODE

The knowledge of the contributions of each of the carrier modes enables a simplified, yet physically understandable, model of the transmission behaviour to be proposed. Since the zero-order carrier modes make very little contribution, they can be neglected. The energy is then assumed to be transmitted entirely by the S_1 and A_1 modes, each contributing approximately equally. Immediately after their excitation, these two carrier modes have opposite phases to each other in the top adherend - figure 9 shows that S_1 retains the same sign of the in-plane displacement throughout the thickness of the joint, whereas A_1 has a

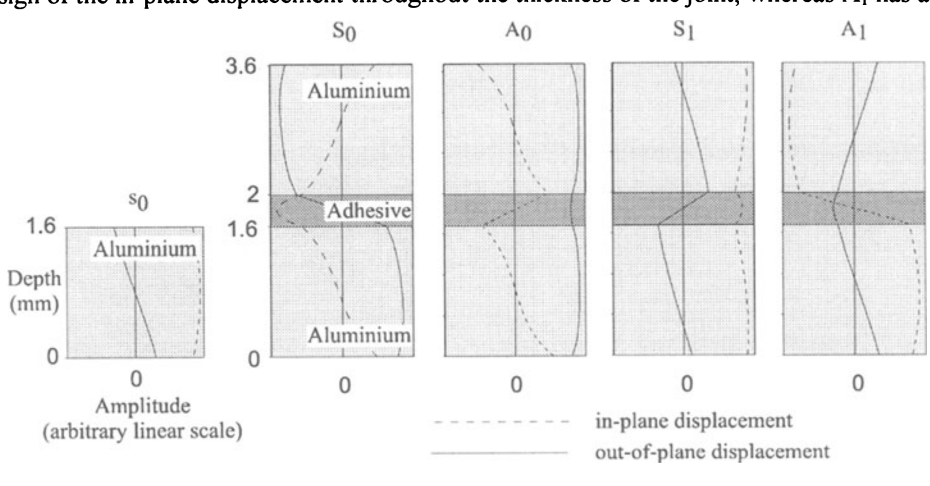

Figure 9. Displacement mode shapes in aluminium plate and in overlap region.

change of sign between top and bottom adherends. Therefore initially they have a cancelling effect on each other in the top adherend. However as they travel along the joint, their interference with each other is modified because their phase velocities (Figure 6) are different. Thus ultimately the strength of the excitation of the s_0 mode in the receiver plate (this is the top plate) depends on the interference between the S_1 and A_1 modes at the end of the overlap region. The amplitude of the transmitted s_0 mode, A_t, can be expressed as follows:

$$A_t = A_{S1}\, e^{i(\omega t - k_1 x)} - A_{A1}\, e^{i(\omega t - k_2 x)} \tag{2}$$

where A_{S1} and A_{A1} are the amplitudes of the received s_0 mode which would be expected separately for the S_1 and A_1 carrier modes, k_1 and k_2 are the wavenumbers of the S_1 and A_1 modes respectively, ω is the frequency and x is the bond length.

If the bond length is very short then the S_1 and A_1 modes effectively cancel, and very little s_0 is transmitted. On the other hand, for a certain length of bond, they will be in phase and add perfectly, so generating a maximum amplitude of s_0. This trend can be seen in Figure 5, where the transmission coefficient for this joint (0.4 mm thick) increases steadily with the bond length. In this case the phase velocities of the two carrier modes are very similar so the bond length would need to be approximately 500 mm for maximum transmission.

An example of an estimate using this simple model is shown in Figure 10(a). Equation (2) was evaluated for a joint with a bond length of 500 mm, for a range of frequencies covering the bandwidth of the 625 kHz signal used in the study. As explained above, this long bond length is optimum for the transmission of s_0 across the joint. However the main reason for using a long length was to enable comparison to be made with a complete Finite Element simulation of the full joint. The long overlap length causes the reverberations in the joint, which have not yet been considered in the simple model, to be delayed in time, and they are therefore easily gated out in the received signal. The figure thus shows the spectra of the incident signal, the simplified model and the full Finite Element model. The spectra show clearly that the simple model provides a very reasonable estimate of the transmission behaviour.

The reverberations along the length of the overlap region may also be included in the simplified model by considering the reflection coefficients of the carrier modes from the ends of the overlap region, and adding the contribution to the transmitted s_0 mode after each subsequent reverberation. There is not sufficient space here to present the details of this extension to the model. However, Figure 10(b) shows the results of including reverberations in the model, for the same joint which was used for Figure 10(a). This illustrates the characteristic interference effect in the spectrum, as was seen in the 2DFFT plot in Figure 4. The spectrum (not shown) for the full Finite Element model is very similar

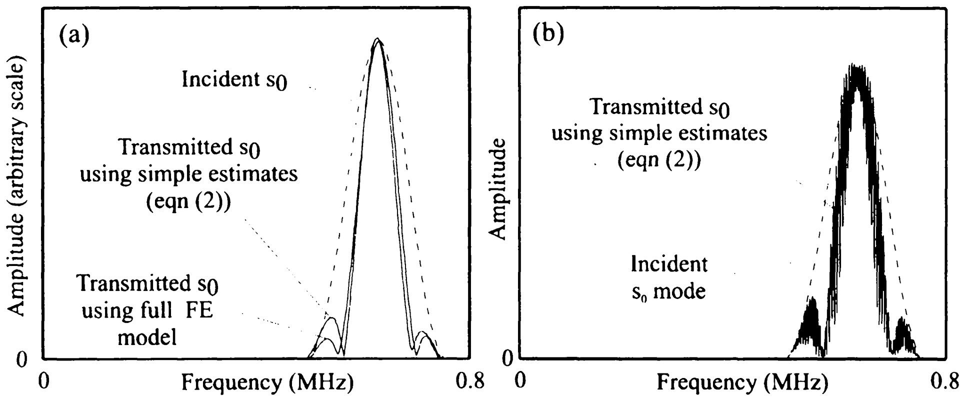

Figure 10. Transmission spectra for joint with 500 mm bond length; (a) without reverberations, (b) including reverberations.

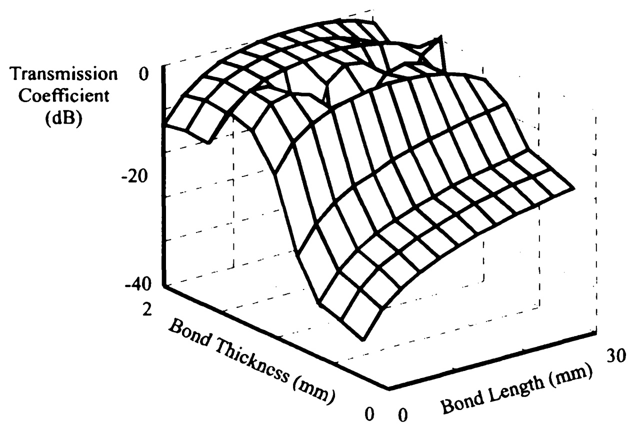

Figure 11. Power transmission coefficient for s_0 mode, estimated using simple model.

when its reverberations are included.

Finally, Figure 11 shows a very simple estimate of the power transmission coefficients of the s_0 mode, constructed for ranges of bond thicknesses and lengths using equation (2). The transmission contributions A_{S1} and A_{A1} were assumed to be equal, and k_1 and k_2 were calculated solely for the centre frequency in each case. There was thus no reliance on the detailed results of the two-stage Finite Element study. Reverberations were neglected. Despite the very crude nature of this estimate, the power transmission surface shows trends which are similar to the results of the full models in Figure 5.

CONCLUSIONS

The transmission of Lamb modes across adhesively bonded joints yields complicated signals, from which it is not straightforward to determine the influence of the parameters of the joints. Finite Element studies of the transmission of the s_0 mode across a lap joint have been performed and have provided some explanation of the phenomena which occur. The key features are multi-mode propagation in the overlap region, reverberation over the length of the overlap region, and multi-mode excitation in the receiver plate.

A simple, yet physically understandable, model to explain the transmission across the joint is proposed. It is shown that the principal modes which carry the energy in the overlap region are those whose displacement mode shapes best match those of the incident mode in the transmitter plate. It is also found that the strength of the overall transmission is governed by the interference between the modes in the overlap region. Estimates made with the simple model agree well with predictions made with full Finite Element models of the joints.

REFERENCES

1. C.C.H. Guyott, P. Cawley, R.D. Adams, J. Adhesion 20, 129 (1986).
2. R.B. Thompson and D.O. Thompson, J. Adhesion Sci. Technol. 5, 583 (1991).
3. S.I. Rokhlin, J. Acoust. Soc. Am. 89, 2758 (1991).
4. S.I. Rokhlin, S. Meng, L. Adler, Mater. Eval. 47, 935 (1989).
5. R.E. Challis, C.P.D. Todd, "Estimation of bond line dimensions in adhered metal joints using ultrasonic Lamb waves: developments using artificial neural networks", in these proceedings.
6. D. Hitchings, *FE77 User Manual* (V. 2.40, Imperial College internal report, 1995).
7. M.J.S. Lowe, IEEE Trans. UFFC 42, 525 (1995).
8. B.N. Pavlakovic, M.J.S. Lowe, D.N. Alleyne, P. Cawley, in *Review of Progress in Quantitative NDE*, Vol. 16, eds. D.O. Thompson and D.E. Chimenti (Plenum Press, New York, 1997), Vol. 16, p. 185.
9. D.N. Alleyne, P. Cawley, J. Acoust. Soc. Am. 89, 1159 (1991).